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Microbial fuel cell energy harvesting using synchronous flyback converter

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HIGHLIGHTS

- Novel MFC energy harvesting scheme using a synchronous flyback converter.
- Improved harvesting efficiency using transformer based synchronous converter.
- Non-inverting hysteresis controller for adaptive harvesting with fewer components.

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ABSTRACT

Microbial Fuel Cells (MFCs) use biodegradable substrates, such as wastewater and marine sediments to generate electrical energy. To harvest more energy from an MFC, power electronic converters have recently been used to replace resistors or charge pumps, because they have superior controllability on MFC's operating point and higher efficiency in energy storage for different applications. Conventional diode-based energy harvesters suffer from low efficiency because of the energy losses through the diode. Replacing the diode with a MOSFET can reduce the conduction loss, but it requires an isolated gate signal to control the floating secondary MOSFET, which makes the control circuitry complex. This study presents a new MFC energy harvesting regime using a synchronous flyback converter, which implements a transformer-based harvester with much simpler configuration and improves harvesting efficiency by 37.6% compared to a diode based boost converter, from 33.5% to 46.1%. The proposed harvester was able to store 2.27 J in the output capacitor out of 4.91 J generated energy from the MFC, while the boost converter can capture 1.67 J from 4.95 J.

1. Introduction

Microbial fuel cell (MFC) is an emerging technology that uses microorganisms to generate electrical energy from biodegradable substrates, such as municipal and industrial wastewater as well as marine sediments. The oxidation of organic substrates by microbial extracellular electron transfer results in electron transfer to the anode electrode, and current is generated when the electrons further flow to the cathode through the external circuit connection [1–3]. The power output from MFC systems has been improved significantly due to the development of new materials and reactor configurations, and in some areas such as remote sensing, the MFC has been considered as a viable power source [4–8].

One of the main challenges facing MFC technology is how to make power generation more efficient. Because the output power of an MFC is low and difficult to use directly [9,10], advanced power conversion techniques need to be developed to maximize energy harvest [11–13]. The harvesters that have been studied in recent years largely fall into two categories: passive and active harvesters.

Passive harvesters extract energy with passive electrical components, such as resistors, capacitors, and charge pumps. A resistor is the simplest energy extraction device and has been widely used [14–16]. It is well known that the extracted power is maximum when $R_{ext} = R_{int}$, but it should be noted that all of the extracted energy will be dissipated as heat instead of being used or stored. A supercapacitor is a better option than the resistor because it actually stores the energy instead of burning it. Different combinations have been used, but they share the idea of connecting the capacitors directly to the MFCs [4,5,7,17]. The problem is that the operating point of the MFC changes when the capacitor voltage changes

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as the energy balance varies. Therefore, it is practically impossible to maintain the operating point at the maximum power point (MPP) with direct connection of capacitors, where an MFC reactor can generate the maximum power possible for a given condition. A charge pump is a more advanced solution than directly-connected capacitors [4,7,18], because it consists of capacitors and switches that can increase the output voltage from a low input voltage and maintain it at a certain fixed level. Although charge pumps do contain active components, their controllability is insufficient to meet specific MFC requirements. Moreover, the availability of off-the-shelf charge pumps for MFCs is very limited, and their current level is low (e.g., <500 μA) to avoid the input voltage drop, which makes the harvesting efficiency low [19].

Active harvesters use power electronics converters and actively control the operating point and the energy extraction of an MFC. Active energy extraction is the most effective way to harvest the energy from low-power sources including MFCs [18,20–22]. The energy can be stored in a capacitor and the MFC voltage is controlled at any operating point, e.g., MPP. Power electronics converters using semiconductor devices switching at high frequency can provide far better controllability on power flow than passive components, which results in significantly improved energy extraction efficiency. For example, a diode-based boost converter operating in MPP can harvest 76 times more energy than the charge pump that is commonly used in MFC studies [19]. It also is beneficial to implement a controller that tracks the varying MPP [13]. If a double-layered scheme is used, the improved harvesting efficiency, increased capacity, and regulated output voltage can be simultaneously achieved [23]. Although the active harvesting approach has challenges such as complex circuitry and control, and higher loss and power consumption of the control system, the benefits in performance and efficiency outweigh the disadvantages. The elements of power converters, such as inductance, duty ratio, and the switching frequency, that affect the energy extraction were investigated in Ref. [24].

The boost converter is one of the widely used power converters for MFC energy harvesting because of its simple structure and the need to increase the output voltage of the MFC [20–22,25]. A conceptual boost converter schematic is shown in Fig. 1. When the switch Q_1 is closed and the switch Q_2 is open, the current will flow through the inductor L. The voltage will be generated across the inductor according to the basic inductance–current voltage relation

$$V_L(t) = L\frac{\mathrm{d}i_L(t)}{\mathrm{d}t} \tag{1}$$

where V_L is the voltage across the inductor L, and i_L is the current passing through it. Then the switches Q_1 and Q_2 should open and close, respectively, to forward the energy stored in the inductor to the load. During this time the current will start to flow through the switch Q_2 to charge the capacitor and the charging voltage will be given as

$$V_C = V_{\mathrm{in}} + V_L \tag{2}$$

where V_L is the inductor voltage achieved on the first time period. When all of the energy in the inductor is discharged, Q_1 and Q_2 should close and open to start the energy extraction. Switching between these two modes in high frequency will allow the energy to be extracted and stored in the capacitor with a boosted voltage.

For the simplest configuration, a diode is used for Q_2. A diode conducts or blocks the current path according to the bias voltage across it (forward- and reverse-biased). However, unlike the resistors, the diode has a fixed voltage drop (V_F, generally 0.4–0.7 V

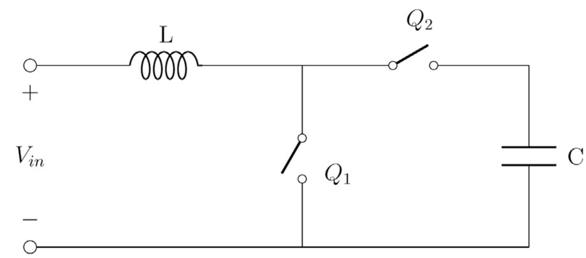

Fig. 1. Schematic diagram of boost converter.

regardless of the current magnitude) when it is forward-biased and conducting. Hence, the loss of the diode is given as

$$P_D = V_F I_L \tag{3}$$

and it is very high considering the low power output of MFC [19], which is a critical drawback of the diode-based boost converter. To avoid the high loss of the diode, a synchronous boost converter can be used [25]. The synchronous boost converter replaces the diode with a MOSFET, and it reduces the overall loss significantly due to the MOSFET's low on-resistance (order of mΩ for low-power MOSFETs). However, the problem of using the synchronous boost converter is that the MOSFET will become a floating switch, which, unlike the diode, requires an isolated source to turn it on and off. Transformers have been used to drive the MOSFET in the synchronous boost converter, but the circuitry and control becomes quite complex.

In this study, a synchronous flyback converter was applied to MFC energy harvesting to simplify the control circuitry and improve the efficiency. The flyback converter is a viable alternative of the boost converter, because its energy transfer transformer can readily be used to drive the secondary floating switch. Hence, the synchronous flyback converter will be more efficient by eliminating the diode and using the main transformer for the gating signal as well as power transfer. Its energy harvesting performance at the MPP was compared to that of the boost converter.

2. Methods and materials

2.1. Microbial fuel cell

A two-chamber cube-shaped MFC was used in the study. A cation exchange membrane (CMI-7000, Membranes International, NJ) was used to separate the anode and cathode chamber, and each chamber's empty volume was 150 mL. Graphite brushes and carbon cloth were used as the anode and cathode material, respectively. Anolyte was acetate-based medium containing 1.25 g CH_3COONa, 0.31 g NH_4Cl, 0.13 g KCl, 3.32 g $NaH_2PO_4 \cdot 2H_2O$, 10.32 g $Na_2HPO_4 \cdot 12H_2O$, 12.5 mL mineral solution, and 5 mL vitamin solution per liter [26,27]. Phosphate buffered potassium ferricyanide solution (50 mM) was used as the catholyte to minimize the cathode effects on system performance. The reactor was initially operated in fed-batch mode until repeatable voltage was obtained, then they were switched to continuous-flow operation by recirculating anolyte with a 1000 mL reservoir at a flow rate of 45 mL min^{-1} and recirculating catholyte with another reservoir at a flow rate of 114 mL min^{-1}, respectively [19,31].

2.2. Synchronous flyback converter

The flyback converter is derived from the boost converter, but uses a transformer to store energy instead of the inductor in the boost converter. The transformer also offers voltage boost and

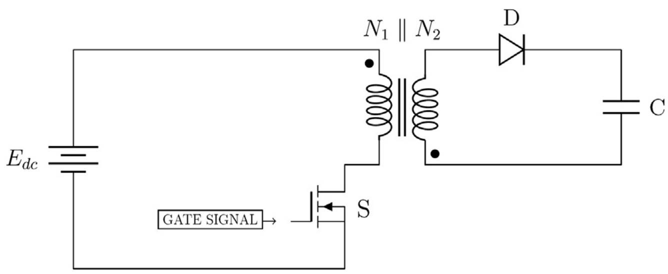

Fig. 2. Synchronous flyback converter.

galvanic isolation between input and output, which can be used to drive the secondary MOSFET. A schematic of the synchronous flyback converter is shown in Fig. 2. A self-synchronized gate driver circuit [28] is used to drive the primary and secondary MOSFET switches in this study. The gate driver uses the voltage from the transformer and the direction of secondary current.

The operation of the flyback converter is defined by two modes: On-State and Off-State, in which the converter extracts energy from the MFC and transfers the energy to the capacitor, respectively. When the switch S_1 in Fig. 2 closes, the primary winding of the transformer is connected to the MFC's positive terminal. During this time, the secondary switch S_2 is open. The input voltage will then appear across the primary winding and the current will flow through according to the current–voltage relation (1). The flux will be established in the transformer core by the primary current only because there is no secondary current. This is the On-State mode and Fig. 3 shows the current carrying part of the circuit during this mode of operation. The energy will be stored in the magnetic field and it can be calculated using

$$E_{\text{stored}} = \frac{1}{2} L_P I_P^2 \tag{4}$$

where I_P denotes the magnitude of the primary current at the end of the conduction period. At the end of the On-State mode, the switch S_1 opens and cuts off the current in the primary windings. When the current path is open, the voltage of the primary winding will be reversed according to the Faraday's law. The voltage polarity of the secondary side will also be reversed. Simultaneously the secondary switch S_2 has to be closed to allow the energy stored in the magnetic field to discharge through the secondary winding of the transformer and charge the capacitor. This switching needs to be done by the gate driver in the synchronous converters, while in diode-based converters, the diode is automatically conducting because it is forward-biased when the primary switch S_1 opens. This is the Off-State mode of operation, and the equivalent circuit can be seen in Fig. 4. The converter repeats these two modes at high frequency and the duration of each mode is determined by duty ratio from the controller, which allows adjustment of the MFC operating point.

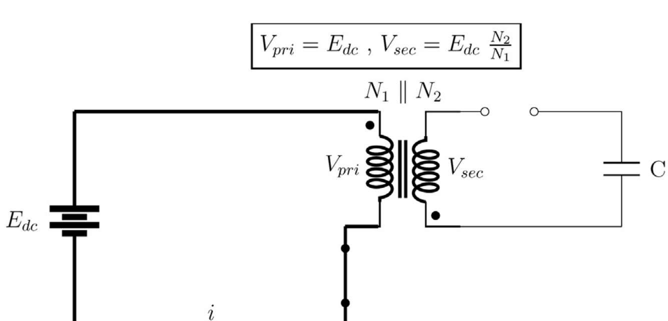

Fig. 3. Flyback converter operation mode I.

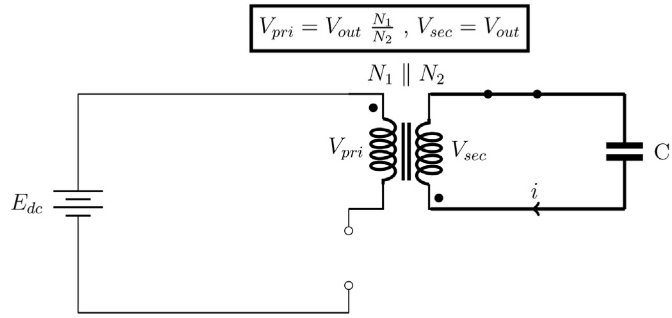

Fig. 4. Flyback converter operation mode II.

Another major advantage of using a flyback converter for the low-power energy harvester is that the power can be transferred with a higher voltage. More turns in the secondary windings of the transformer than the primary boosts the secondary voltage. For a given power transferred through a transformer with an 1:N turn ratio, the secondary voltage and current are N times larger and smaller respectively than that of the primary. Smaller secondary current reduces the secondary copper loss, which is given as

$$P_s = I_s^2 R_s \tag{5}$$

where I_s and R_s is the secondary current and resistance. For example, if the secondary winding is doubled, the resistance will also be doubled. But the current will be reduced in half, which will decrease the loss by half. Hence, the efficiency can be improved as the turn ratio increases.

2.3. Hysteresis controller

To be able to maintain the MFC voltage at the desirable level, the hysteresis controller can be used. The inverting hysteresis controller has been used with the boost converter in Refs. [13,20,23,25]. Although the scale factor is simpler, a transistor must be added to invert the output signal when using the inverting hysteresis controller. This transistor can be eliminated if the hysteresis controller is configured with a non-inverting circuit. The non-inverting hysteresis controller shown in Fig. 5 can maintain the voltage of the MFC at the desirable level with fewer components.

The resistors R_2 and R_4 in Fig. 5 are chosen to be variable resistors to change the hysteresis band, which controls the output voltage of the MFC and the energy harvesting frequency. The upper

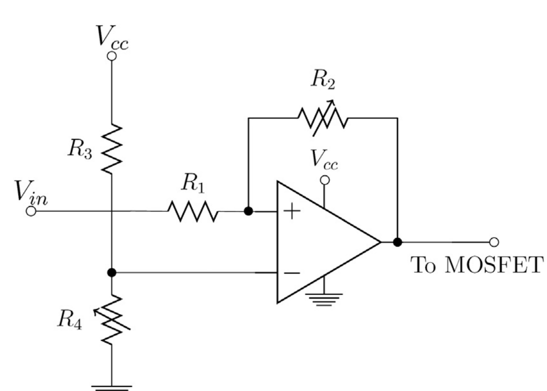

Fig. 5. Non-inverting hysteresis controller.

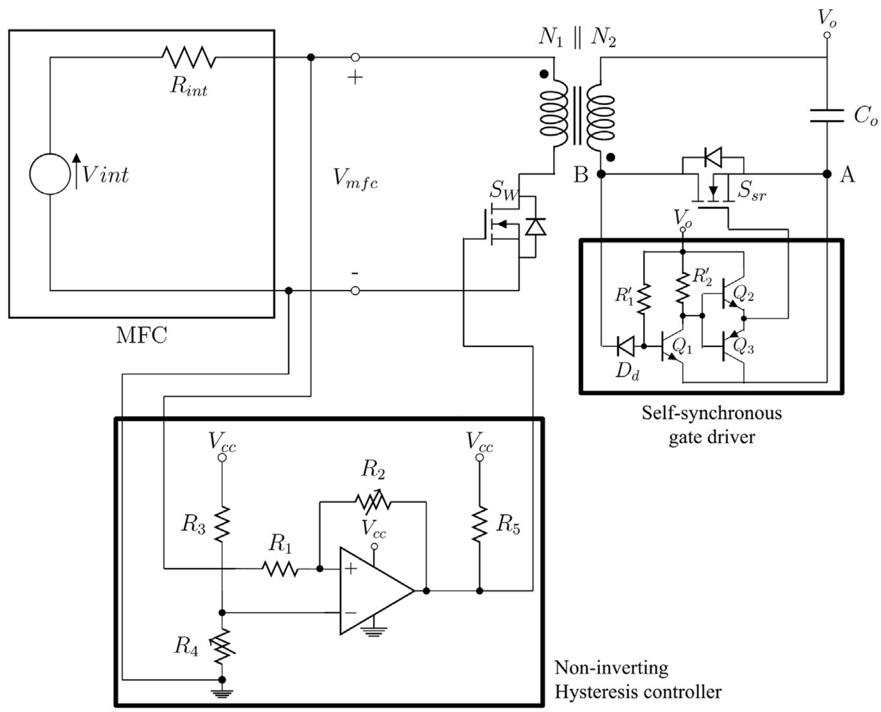

Fig. 6. Schematic of proposed MFC energy harvesting system.

and lower threshold voltages ($V_{th\text{-}H}$ and $V_{th\text{-}L}$, respectively) determine the hysteresis band. For the proposed circuit in Fig. 5, the values of the $V_{th\text{-}H}$ and $V_{th\text{-}L}$ are given as follows.

$$V_{th-H} = \frac{(R_1+R_2)R_4}{(R_3+R_4)R_2}V_{CC} \tag{6}$$

$$V_{th-L} = \left\{\frac{(R_1+R_2)R_4}{(R_3+R_4)R_2} - \frac{R_1}{R_2}\right\}V_{CC} \tag{7}$$

$$\Delta V = V_{th-H} - V_{th-L} \tag{8}$$

When the MFC voltage reaches the $V_{th\text{-}H}$, the controller turns the MOSFET on, and when the MFC voltage hits the $V_{th\text{-}L}$, the MOSFET is turned off. With this simple hysteresis controller, the frequency of energy extraction, in other words, the duty ratio of the converter is inherently adapted to the MFC condition. If the MFC has strong bacteria activity, the voltage will recover quickly when the MOSFET is off, hence turns on the switch faster. Or, the controller gives enough recovery time to the reactor when the voltage restores slowly.

The overall schematic of proposed control scheme is shown in Fig. 6.

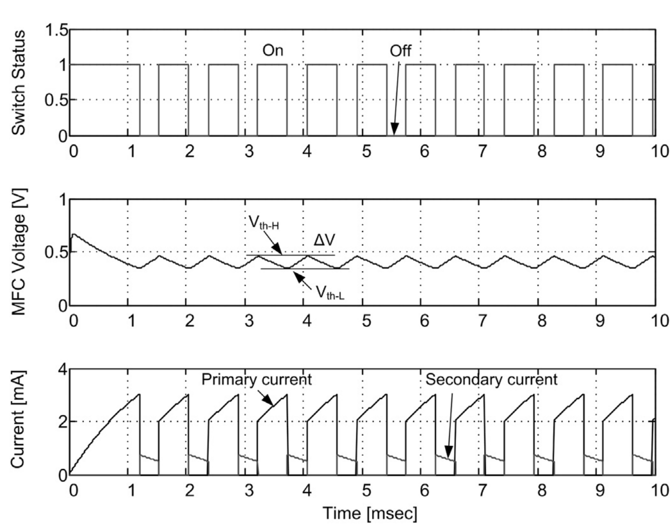

Fig. 7. Computer simulation result.

2.4. Computer simulation

After choosing the hysteresis controller and the self-synchronized gate driver for flyback converter to harvest the energy from the MFC, a computer simulation was performed to verify the proposed approach. The well-known MFC model with a thermoelectric voltage source and an internal series resistance was used [29,30]. In this simulation, 0.7 V and 120 Ω were chosen for V_{int} and R_{int}, respectively. A 19 μ s time-constant for MFC voltage dynamics was included. The simulation code was developed in Matlab and the results are shown in Fig. 7.

The first waveform in Fig. 7 is the primary MOSFET gate signal, which is controlled by the hysteresis controller. The second waveform is the MFC output voltage: initially the hysteresis controller will turn the primary MOSFET on, and the current will flow through

Table 1
Experimental system parameters.

Parameter	Value	Parameter	Value	Parameter	Value
Transformer turn-ratio	1:4 (50:200)	R_1	500 Ω	R'_1	1 MΩ
Transformer primary inductance	7 mH	R_2	500 kΩ (variable)	R'_2	100 kΩ
MOSFETS	4906NG	R_3	10 kΩ	D_d	1N755A
Comparator	LM2903	R_4	5 kΩ (variable)	Q_1, Q_2	PN2222A
Capacitor	1 F, 2.5 V	R_5	1 kΩ	Q_3	PN2907A

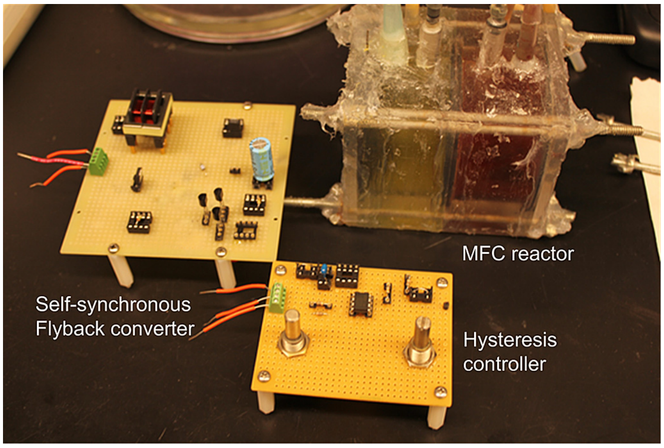

Fig. 8. Experimental energy harvesting system.

the primary winding. The voltage of the MFC will decrease as the current increases, and when the MFC voltage reaches the lower threshold voltage the hysteresis controller will turn the primary MOSFET off. The synchronous gate drive will turn the synchronous MOSFET on and off depending on the current direction on the secondary side of the transformer [28]. The third waveform represents the primary and the secondary currents and it can be seen that the secondary current magnitude depends on the turn ratio of the transformer; in this study it is smaller because the turn-ratio is 1:4 to increase the output voltage.

3. Experimental

3.1. Synchronous flyback converter

The overall system schematic of the proposed MFC energy harvesting system shown in Fig. 6 was implemented in actual hardware experimental setup. The flyback transformer was built using ferrite cores (B66315-G0000-X130, EPCOS AG, Germany) and transformer winding machine (Bobineer, Gorman Machine Co., MA). The primary inductance is an important parameter because it determines the energy extraction frequency. For this experiment, it was chosen to have low inductance to reduce the number of turns and the resistance of the windings. The 50-turn primary winding has an inductance of 7 mH and 3.2 Ω resistance. The transformer turn ratio is also important because it determines the secondary voltage and current. Although the power loss gets lower, the voltage drop would be too much for MFC applications if the turn-ratio is too high. The turn ratio in this experiment was 1:4.

N-channel MOSFET 4906NG (ON Semiconductor, AZ) was used on both switches, which has 6.5 mΩ on-resistance at 4.5 V V_{GS}. Comparator LM2903 (Texas Instruments, TX) is used for hysteresis controller. Generic PN2222A NPN and PN2907A PNP transistors were used for the transistors on the synchronous gate driver circuit. The diode 1N755A (Fairchild Semiconductor, CA) was also used as

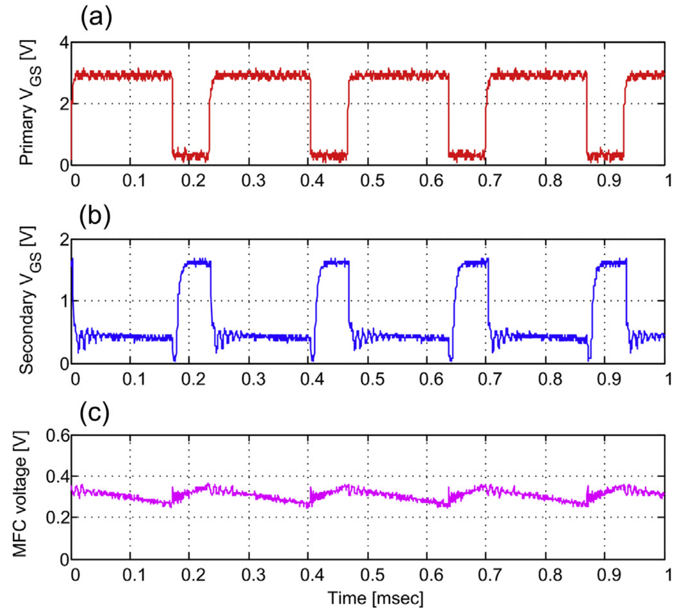

Fig. 9. Self-synchronous flyback converter experiment waveforms. (a) Primary switch state. (b) Synchronous switch state. (c) MFC voltage.

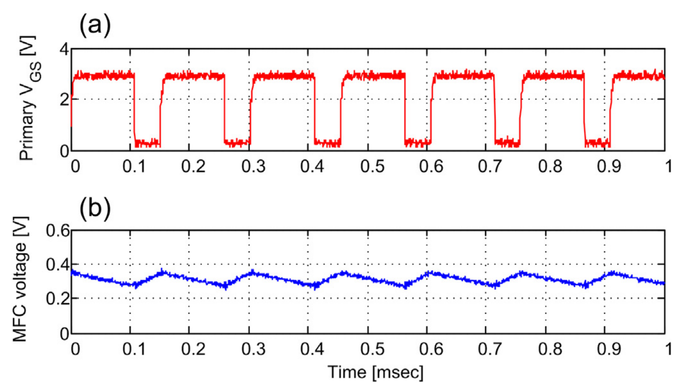

Fig. 10. Boost converter experiment waveforms. (a) Primary switch state. (b) MFC voltage.

D_d in the circuit. The resistor R_1' must be very high to limit the current at a level that is just enough to drive the transistor Q_1. The resistor R_2' should also be high enough so that the current is limited when the transistor Q_1 is on. The values of the parameters that were used in this experiment are listed in Table 1.

3.2. Boost converter

To compare the performance of synchronous flyback converter, diode based-boost converter was used. To make a fair comparison,

Table 2
Experimental result: self-synchronous flyback converter and boost converter.

Time [min]	Flyback converter					Boost converter				
	V_{MFC} [V]	I_{MFC} [mA]	V_C [V]	Efficiency [%]	F_{sw} [kHz]	V_{MFC} [V]	I_{MFC} [mA]	V_C [V]	Efficiency [%]	F_{sw} [kHz]
5	0.302	10.8	0.82	34.2	5	0.311	10.9	0.89	38.9	6
10	0.309	10.7	1.27	47.4	4.2	0.312	10.7	1.30	44.8	6.3
15	0.307	10.7	1.61	48.9	3.6	0.312	10.5	1.56	37.0	6.4
20	0.307	10.7	1.89	49.7	3.3	0.312	10.5	1.71	24.7	6.5
25	0.310	10.5	2.13	50.3	3	0.311	10.4	1.83	22.0	6.5

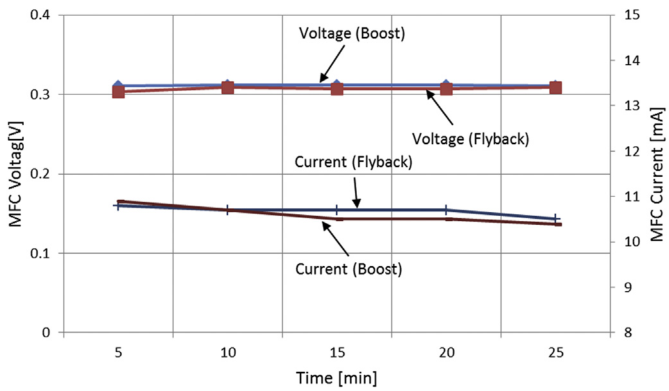

Fig. 11. MFC voltage and current of flyback and boost converter experiments.

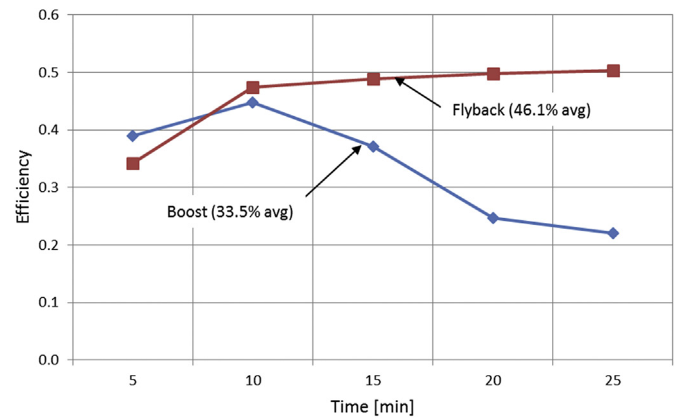

Fig. 13. Energy harvesting efficiency of flyback and boost converter experiments.

the two converters have similar components. The inductor in the boost converter was built using the same transformer core. This inductor has same parameters with the primary side of flyback transformer: 7 mH inductance and 3.2 Ω resistance. Although this inductor is not efficient because of the high resistance compared to the one used in Refs. [20], it was used to compare with the flyback converter. Same MOSFET has been chosen with the 1N755A diode to build the diode-based boost converter. Experimental systems are shown in Fig. 8.

4. Results and discussion

The flyback- and boost-converter-based harvesting systems were applied to an MFC reactor by connecting the MFC with the non-inverting hysteresis controller. Both converters were tested at the same conditions to make a side-by-side comparison. Energy from the MFC was harvested by the converter and stored in an output capacitor. The readings were taken at 5-min interval for MFC voltage, MFC current, output capacitor voltage, and switching frequency. The instantaneous waveforms were recorded using Tektronix TPS2012 oscilloscope. The measurements and the calculated efficiency are shown in Table 2 and Figs. 9 and 10.

The MFC voltage and current from both converters are shown in Fig. 11. Similar MFC operating voltage and current amplitude show power inputs for both converters are similar. Fig. 12 shows that the synchronous flyback converter charged the output capacitor faster than the boost converter due to the improved efficiency in the secondary circuit, which can be clearly seen from Fig. 13. The synchronous flyback converter has higher efficiency than the boost converter after 10 min of operation, when the synchronous driving circuit started to drive the synchronous MOSFET. In our experimental setup, the diode-based boost converter showed significant efficiency drop because the diode loss takes more portion of the transferred energy that is decreasing as the capacitor voltage increases. The synchronous flyback converter can avoid this issue because the secondary voltage is 4 times higher because of the 1:4 turn ratio and the MOSFET conduction loss is much lower than the diode. Therefore, the synchronous flyback converter can maintain an improved and stable performance. Even if the synchronous driving circuit started to drive the synchronous MOSFET after approximately 10 min, the overall efficiency was improved by 37.6% to reach 46.1% compared to 33.5% for the boost converter. The synchronous flyback converter was able to store 2.27 J out of 4.91 J in the output capacitor while the boost converter harvests 1.67 J from 4.95 J. A synchronous boost converter such as in Ref. [25] can have a similar performance improvement, but it requires much more complex control circuitry.

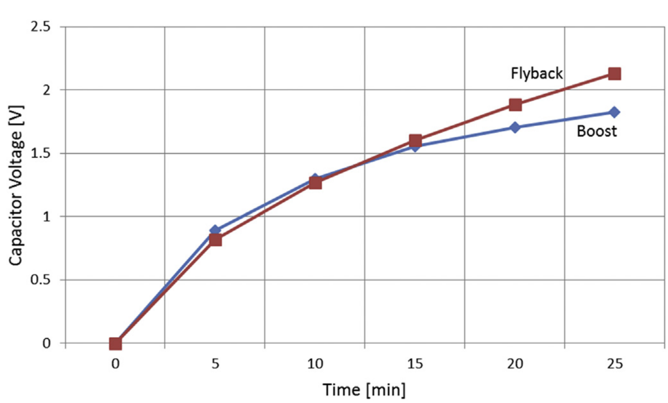

Fig. 12. Output capacitor voltage of flyback and boost converter experiments.

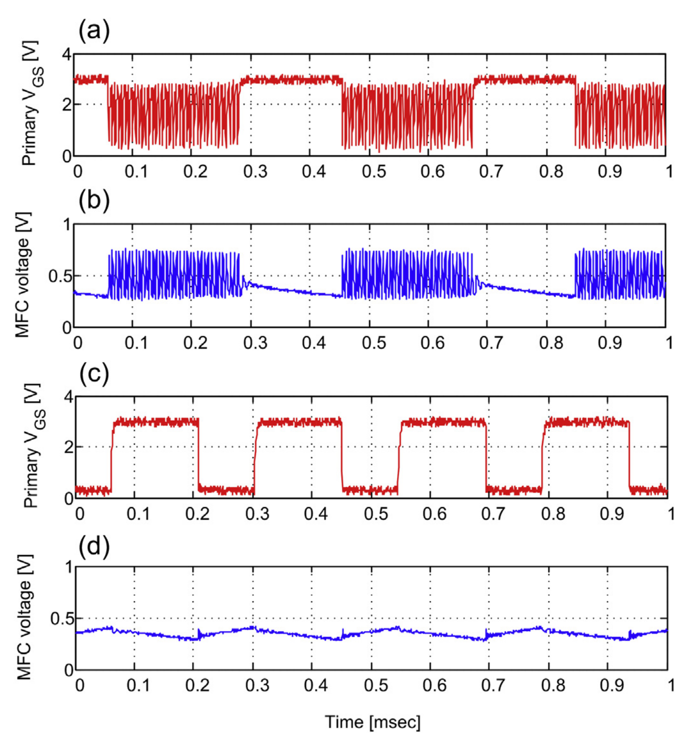

Fig. 14. MFC output voltage ringing. Without filter: (a) Switch state. (b) MFC voltage. With filter: (c) Switch state. (d) MFC voltage.

When the initial version of the circuit was applied to the MFC, the voltage of the MFC started ringing as the switch S_1 turned off, and it became normal when it was on. When the switch is off and the current stops flowing, the voltage increases fast and fluctuates because the MFC voltage is not stiff. This causes the hysteresis controller to oscillate, which will make the ringing worse (Fig. 14(a) and (b)). To solve this problem, the MFC voltage feedback signal was filtered with a 0.1 μF capacitor and the result is shown in Fig. 14(c) and (d).

5. Conclusions

An MFC energy harvesting system based on the synchronous flyback converter was presented in this study. Compared to the boost-converter-based system, the proposed harvesting scheme showed an improved performance with a simpler configuration. Consequently, it enhances the main advantage of using the DC–DC converters, which is the ability to control the operating point of the MFC to maximize the harvesting efficiency and store the harvested energy for practical use. Topics such as self-sustainable harvester without using external power supply for control circuitry and maximum power point tracking (MPPT) scheme for even better harvesting efficiency can be suggested for further investigation.

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